Characterization and control of dynamic lens heating effects under high volume manufacturing conditions

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ABSTRACT

The desire to reduce cost in volume manufacturing has driven up the throughput in the lithographic exposure machines. As a result the power transmitted in the projection optics increases. Although small, the absorption levels in the lens materials are not zero, which leads to localized heating of the lens and hence lens aberrations. To squeeze out the maximum process windows, the pupil shapes have transformed from simple annular shapes to shapes with very concentrated poles. As a result, the exposure energy transported through the lens is no longer equally distributed over the lenses of the projection options. Instead only a fraction of the lens gets to transport the total power. This concentration of power further aggravates the lens heating induced aberrations and enhances the importance of advanced lens heating control schemes which are available on ASML scanners.

To analyze the effects of lens heating on the final imaging, a model was developed by the lens manufacturer Carl Zeiss SMT GmbH, and incorporated into a litho simulation environment by ASML BRION. This tool can be used to analyze the impact of dose/throughput, illumination shapes and reticle layout on aberrations. It provides a means to assess potential lens heating issues even before production masks are manufactured. Moreover, this computational tool opens the possibility to calculate parameters for lens heating correction, rather than measuring them, saving valuable machine time. In this paper, the performance of the novel computational lens heating control is demonstrated on wafer and compared with the traditional way of measuring the relevant parameters. In addition, a modeling study is performed to assess possible lens heating effects for freeform or non-traditional source shapes, thereby demonstrating the advanced correction potential of ASML latest aberration manipulator, called FlexWave™.

Keywords: Lens heating correction, lens heating calibration, FlexWave, FlexRay, freeform illumination

1. INTRODUCTION

1.1 Origin and description of lens heating

Lithographic research and development has reached a very interesting stage. The physical limit of water based immersion ArF lithography has been attained with the accomplishment of full field scanners with a numerical aperture (NA) of 1.35. Such systems are now commonplace in the production flow of all advanced IC manufacturers.

The cost per wafer in high volume manufacturing can be reduced by increasing the throughput of the ArF immersion scanners. In ASML scanners, throughput numbers exceed an amazing 200 wafers per hour. At given exposure dose, the high throughput unavoidably causes heating of the exposure lens through absorption of the laser light. This in turn causes aberrations, or basically phase errors of the light travelling through the projection optics, which may lead to image degradation (CD change, image displacement, loss of patterning fidelity). The lens heating induced aberrations are further aggravated by source shapes with relatively small poles, as currently used in advanced applications, forcing the complete power through only a small section of the optics.

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The gradual warming up of the lens to a certain saturation state is described by the lens heating characteristics, but is also specific to the exact exposure conditions like NA, source shape, reticle and mask pattern diffraction, exposure dose and throughput ("heatload"), resist stack. To describe such lens heating induced aberrated wave front, the phase errors are decomposed in orthogonal Zernike polynomial functions as depicted in Figure 1. Spherical aberration, astigmatism, 4-foil, 6-foil, etc are referred to as 'even aberrations'. These even aberrations result in focus offsets for the different features and thus CD drifts. On the other hand, coma, 3-foil, 5-foil, etc are commonly referred to as 'odd aberrations', whose main effect comes about in feature displacement as well as CD drift.

Since the sources on ASML scanners are point symmetrical around the center of the pupil, the heating induced aberration signature remains predominantly symmetrical as well. This means that the even aberrations will be dominant and only minor contributions are to be expected for the odd aberrations.

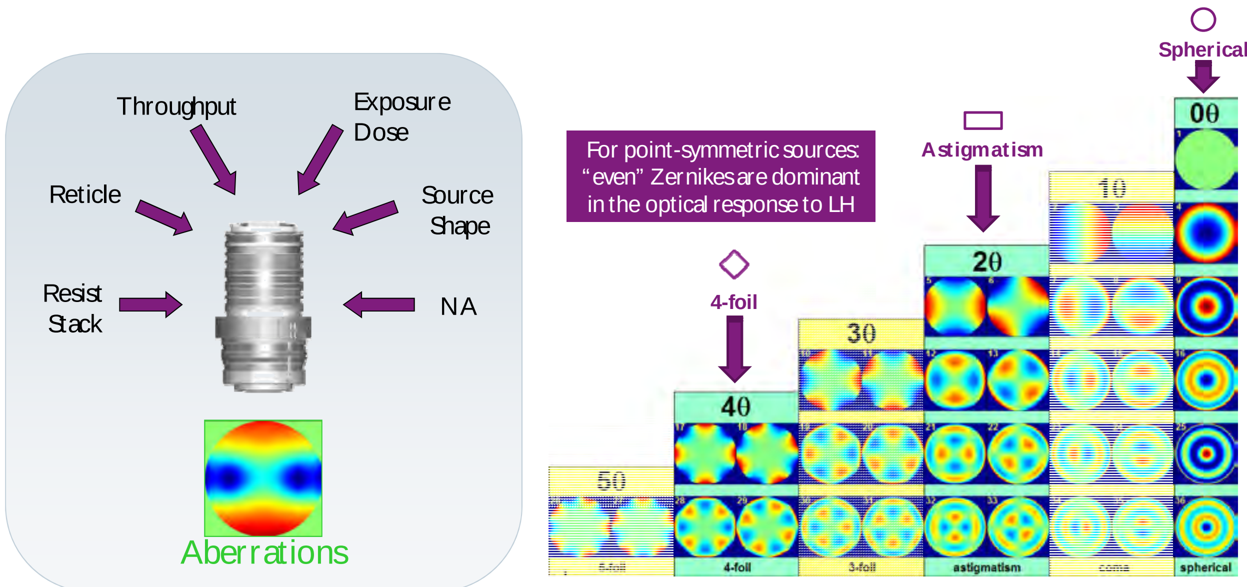

Figure 1. Left: Contributors to the lens heating induced aberrations. Right: Zernike polynomials.

1.2 Lens heating calibration and correction strategies

As the lens heating signature is a strong function of e.g. NA, source shape, and reticle, it is very application-specific. On ASML scanners, two options for application-specific calibration are advised:

- A first option is to perform the calibration on the exposure tool itself, which is called 'Inline calibration', or Advanced Lens Heating Calibration (ALHC). During an ALHC, a normal production lot is exposed, using all production settings: mask, illumination setting, dose, wafer stack, ... During the calibration, the aberrations are monitored over time/heating. This is depicted on the left side of Figure 2. During the actual lot exposure (typically 22-25 wafers), the increasing aberration levels are measured at the end of each wafer exposure. Once the lot is completed, all Zernike drift data is collected and used in a model to predict the Zernike drifts for all subsequent lots that are using the same settings. This allows for applying corrections to counter the effect of Zernike drifts during production. It is clear that the initial calibration will take some additional scanner time, but it can be carried out during normal production.
- A second option is to apply computational application specific calibration (cASCAL), depicted at the right in Figure 2. Zeiss' lens heating model 'DyLHan' is implemented in ASML BRION's LithoTuner software. It is employed to calculate the aberration drift and subsequently provide a set of correction parameters. In this, the software makes use of all the application-specific input: mask information and GDS-II, scanner/lens specific information, exact illumination condition, wafer and resist stack information, wafer layout, dose, and throughput information. In a first step, the full mask diffraction orders are calculated, which are then convoluted with the illumination source to obtain the diffraction pattern. Based on this, the aberration drift is calculated using the implemented dynamical lens heating model. The advantage of computational calibration is that it is a calibration strategy which does not require scanner time.

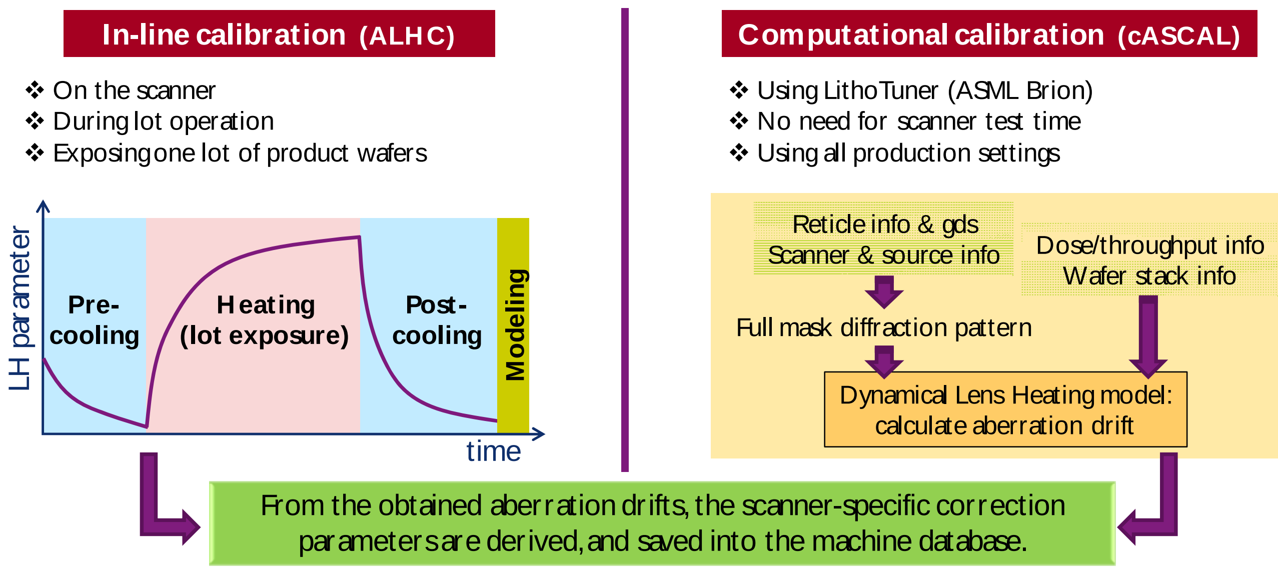

Figure 2. Computational lens heating calibration vs the traditional 'on-tool' inline lens heating calibration.

Both these lens heating calibration methods result in a set of feed forward parameters to drive the different lens heating correction manipulators. These manipulators determine to what extent certain Zernikes can be corrected (correction potential), whereas the modeling only affects the correction accuracy with the manipulator configuration as an input. Over the years, ASML scanners have been equipped with lens heating control manipulators with increasing levels of sophistication and complexity, being able to deal with a larger range of Zernikes or increased correction potential. The latter manipulators are referred to as Advanced Lens Correction (ALC). An example of the use of ALC for lens heating control is given in ref [1].

Recently, ASML introduced an alternative and novel module, called 'FlexWave'™, which is placed into the projection lens near the pupil plane and can provide aberration correction up to Zernike number 64 [2].

With the ability to predict the lens heating induced Zernike drifts, it is possible to assess the severity of lens heating issues generated by extreme sources and exposure schemes. Rotated dipoles are known to be lens heating sensitive. Recently freeform sources have been introduced in the quest for process window improvements in state of the art Source Mask Optimization (SMO) flows [3]. The ASML-BRION simulation environment makes it possible to assess whether or not these types of sources generate specific lens heating issues.

The goal of this work is twofold. First, we provide wafer based proof of lens heating correction, based on both inline and computational calibration. Secondly, we make an assessment of the lens heating signatures induced by non-standard and freeform illumination sources. The latter can be produced by the ASML FlexRay™ illuminator [4].

2. WAFER BASED PROOF OF LENS HEATING CORRECTION BASED ON INLINE AND COMPUTATIONAL CALIBRATION

2.1 Setup of the experiment

An experiment has been set up on an ASML XT:1900i exposure tool (equipped with FlexRay illuminator), with the goal to benchmark the correction based on computational calibration versus that based on inline calibration. In that, the residual hot state wave fronts for both correction strategies will be compared, as well as the residual CD drifts. Note that the lens heating (LH) correction of the used exposure tool is based on the traditional LH correction manipulators, hence not FlexWave.

The considered illumination condition uses a dipole35° Y source with sigma 0.90-0.70 at 1.35 NA. The reticle used for these experiments is a 6% att PSM CDU type reticle containing line and trench patterns through pitch. The reticle contains targets suited for scatterometry, and the ASML YieldStar™ scatterometer is used for the wafer CD measurements. Through pitch, mask CDs were determined to print to a target of 45 nm for horizontal (H) features and 55 nm for vertical (V) features.

Three lots of 49 wafers were exposed at high throughput, using a dose of 30 mJ/cm². These three lots differ by:

- Lot 1: No LH correction is applied
- Lot 2: LH correction based on inline calibration is applied
- Lot 3: LH correction based on computational calibration is applied

From each lot, the 1st 'cold' wafer and the 49th 'hot' wafer is compared in terms of wave fronts and CD drift. To this end, a fast aberration measurement was performed before and after each wafer exposure, which enabled us to monitor the aberration drift during the lot exposures both with and without LH correction.

2.2 Demonstration of lens heating correction in wave front data

Figure 3 shows the absolute values of the measured aberrations after the last wafer of the different lot exposures. Only the measurement results for significant Zernike signals are shown. The values on the Y axis are not shown, as those are not relevant because their value is very application specific (source, mask, dose, throughput, etc…) and therefore should not be the scope of the results. For the aberrations measured from the uncorrected lot (red bars in Figure 3), it is clear that astigmatism is by far the major contributor to the aberration drift, as is to be expected for given dipole source. In addition to the astigmatism, also smaller contributions of spherical aberrations are seen. The blue and green bars in Figure 3 show the measured aberrations in the lens from the lots with LH correction, respectively based on inline and computational calibration. It is clearly seen how the LH correction in both calibration schemes has strongly reduced the aberration fingerprint. Moreover, the result obtained with computational calibration appears comparable to that obtained with inline calibration. The latter is direct proof for the modeling and predictive power of ASML BRION's computational lens heating model.

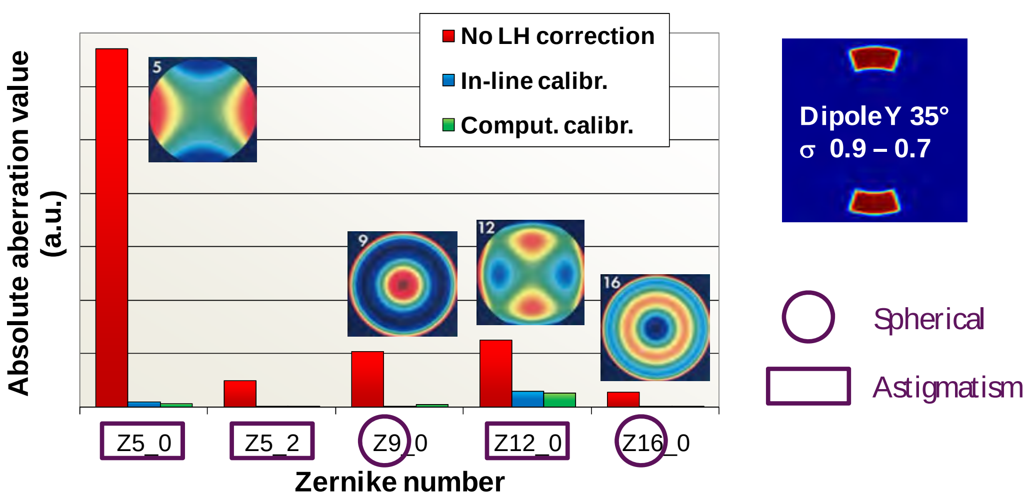

Figure 3. Comparison of hot state aberrations, without correction (red), and with correction from inline and computational calibration (resp. blue and green).

2.3 Demonstration of lens heating correction in wafer CD data

2.3.1 Bossung curves

Next, it is investigated whether the LH correction observed in the measured wave fronts is effectively translated into CD drift correction on the wafers. First, we consider Bossung curves measured from ‘cold’ and ‘hot’ wafers to obtain better understanding of the observed CD drifts. The latter are shown in Figure 4, for a horizontal line on pitch 240 nm and a vertical line on pitch 600 nm. The data shows how the best focus position can be determined on the ‘cold’ wafer of each lot (blue curve). At this best focus position, the CD measurements through pitch will be performed, on all wafers of each lot. Indeed, in production the choice of best focus is fixed throughout the lot. The red curve shows the Bossung lines of the same features, as measured on the ‘hot’ wafer from the lot without LH correction. The effect of the uncorrected astigmatism is clearly visible in the shift of the Bossung lines with opposite sign for the vertical and the horizontal features. Because of this shift, the CD measured at the ‘cold’ best focus position drifts to lower values. The green curve in the graph demonstrates that applying lens heating correction controls the aberrations such that the feature-dependent focus shifts are countered, and the CD at the ‘cold’ best focus maintained.

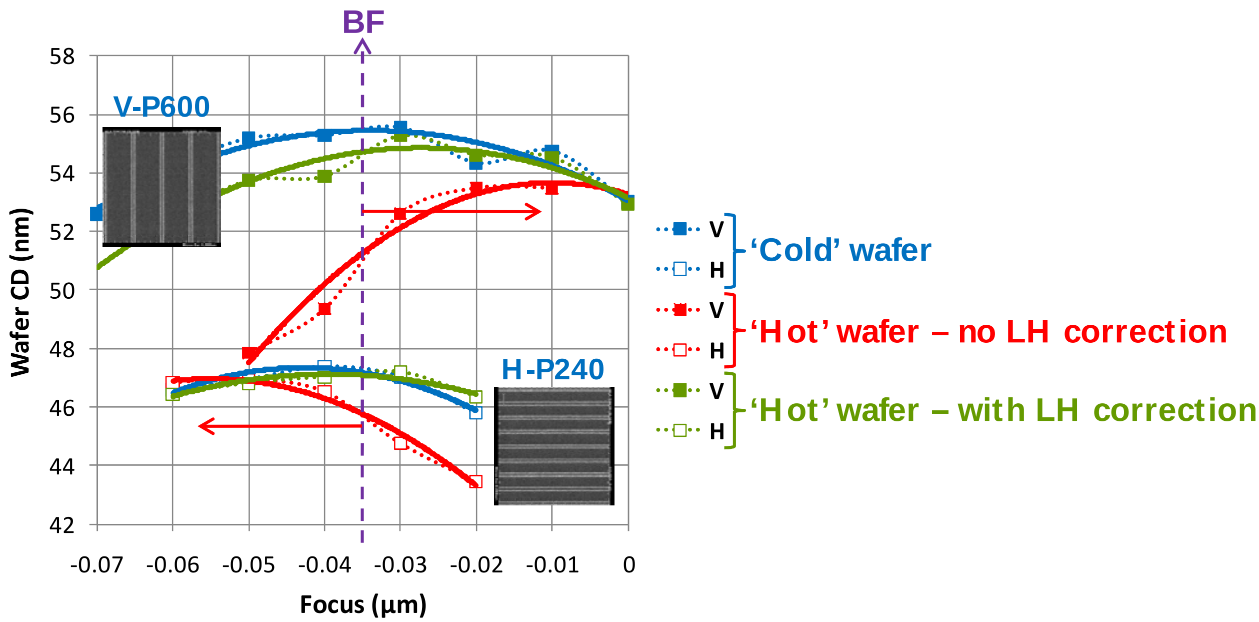

Figure 4. Experimental Bossung lines for lines on a vertical pitch 600 nm and horizontal pitch 240 nm. Blue: on the first wafer (‘cold’) of the different lots. Red: on the last wafer (‘hot’) of the lot without LH correction. Green: on the last wafer (‘hot’) of the lot with LH correction (based on computational calibration).

2.3.2 CD drift of lines and trenches through pitch

The CDs of V and H lines and trenches through pitch are measured on both the ‘hot’ and ‘cold ‘wafer from each of the three lots. Repetitions of the line/trench modules on the mask, in combination with the fast metrology provided by the ASML YieldStar scatterometer enabled to measure these CDs at eight different horizontal positions through the exposure slit. In this way, ‘hot’ minus ‘cold’ CD drifts have been obtained through slit, and this for a wide range of pitches from dense to isolated. The result for the line patterns is shown in Figure 5 below, where the range of different colors in the graphs represents the different pitches. In the situation without correction, CD drifts up to 8~10 nm are seen. The strongest CD drifts are found for the lines on the most isolated pitches, which is logical in that sense that these pitches have the smallest depth of focus. Indeed, in correspondence to Figure 4 above, the steeper slope at the ‘cold’ best focus leads to larger impact on the CD. The signature through slit can largely be explained by the presence of higher order terms through slit, in particular curvature Z5_2 (cfr. Fig. 3). In addition, any focus signature through the slit of the particular scanner will have a magnifying effect on this CD drift.

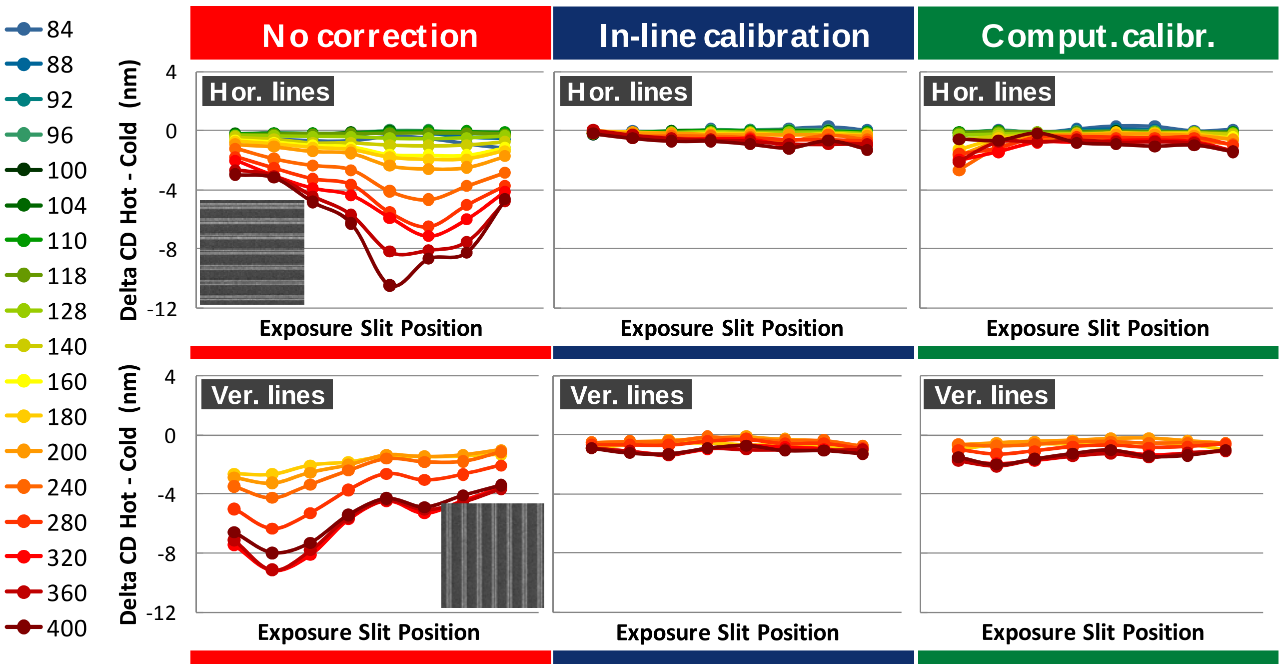

Figure 5. CD drift of lines through pitch, through slit, obtained from subtracting the CD data measured on the 'cold' wafer from that measured on the 'hot' wafer. Left: without applying LH correction. Middle: with LH correction based on inline calibration. Right: with LH correction based on computational calibration.

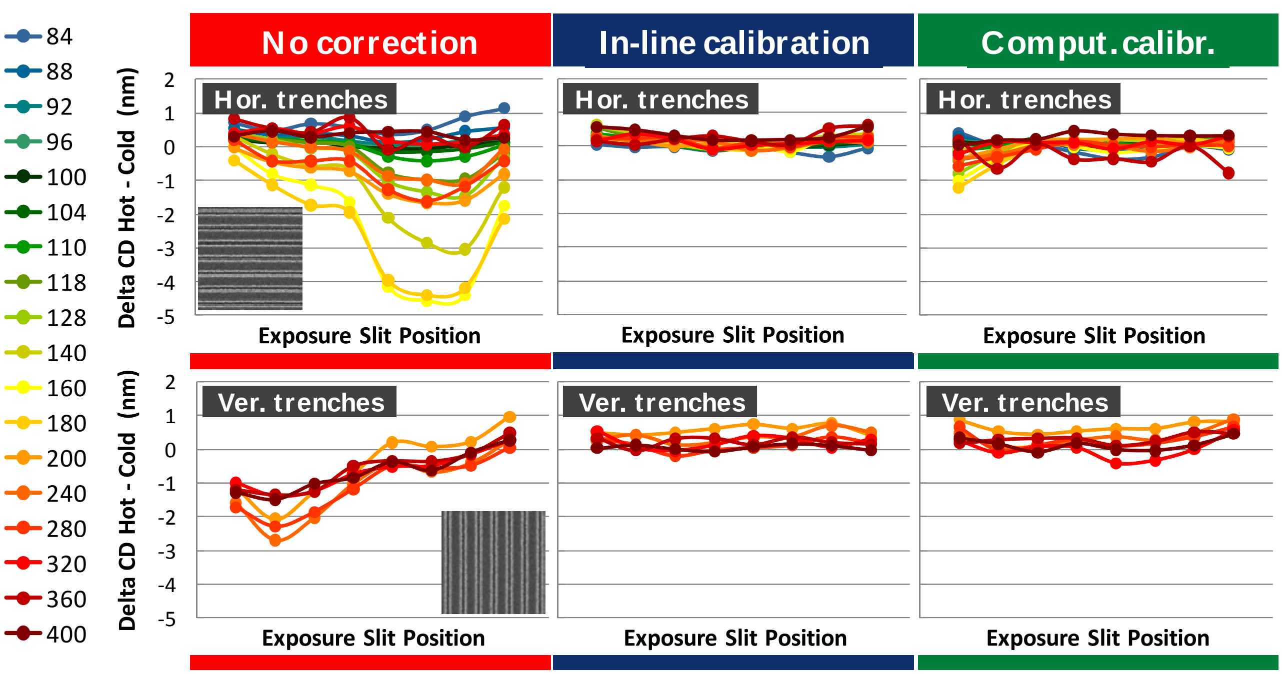

Figure 6. CD drift of trenches through pitch, through slit, obtained from subtracting the CD data measured on the 'cold' wafer from that measured on the 'hot' wafer. Left: without applying LH correction. Middle: with LH correction based on inline calibration. Right: with LH correction based on computational calibration.

More importantly, it can be seen that the measured CD drift through slit in the hot state is much reduced by applying the LH correction, for each pitch and both orientations. In addition, the data shows that the correction based on the computational calibration provides a very comparable result to that obtained using the inline calibration.

An analogous result is obtained for the CD drift measurement for the trenches through pitch on the same wafers. This result is shown in Figure 6. For trenches, the depth of focus behavior through pitch is somewhat different: the horizontal trenches at pitches around the forbidden pitch of 160 nm that have the smallest depth of focus, which leads to the largest CD drift. Apart from this, the findings are the same as for the lines above: LH correction based on computational calibration leads to similar CD drift correction as that based on inline calibration. This demonstrates the applicability of computational calibration, which provides LH correction without need for scanner test time.

3. LENS HEATING AND FREEFORM SOURCES

3.1 Freeform versus standard source shapes (sources with XY symmetry)

In the new process technologies currently being developed, freeform sources are not an exception anymore. The advantages offered by these sources over the more traditional sources are significant enough to pursue them. At the same time, the ASML FlexRay technology for freeform source generation makes the introduction of such sources in a production environment relatively easy.

Figure 7 shows an example of a 22 nm SRAM contact pattern and a corresponding freeform source as it came out of a Source Mask Optimization (SMO) [3]. It is compared to an optimized standard source, namely a CQuad with a 20 deg opening angle. The case described here uses a negative tone developer in combination with a light field reticle to squeeze out the best available process window. The freeform source gave an improvement over the CQuad in terms of process window, MEEF and CDU [3]. However, the light field reticle can make this solution more vulnerable to LH issues.

The lens heating simulation module of ASML BRION was used to comparing the two sources' lens heating characteristics. Figure 7 shows the most important Zernikes induced by these sources side by side, for a given light field contact mask. As the pitch in X and Y directions is different in the layout, the freeform source has light intensity distribution which is different in X and Y directions, causing the appearance of Z5 in its LH response. The CQuad being perfectly symmetrical over 90 degrees rotation angles does not cause any significant Z5 term, but excites the 4-foil terms to larger amount than the freeform source does.

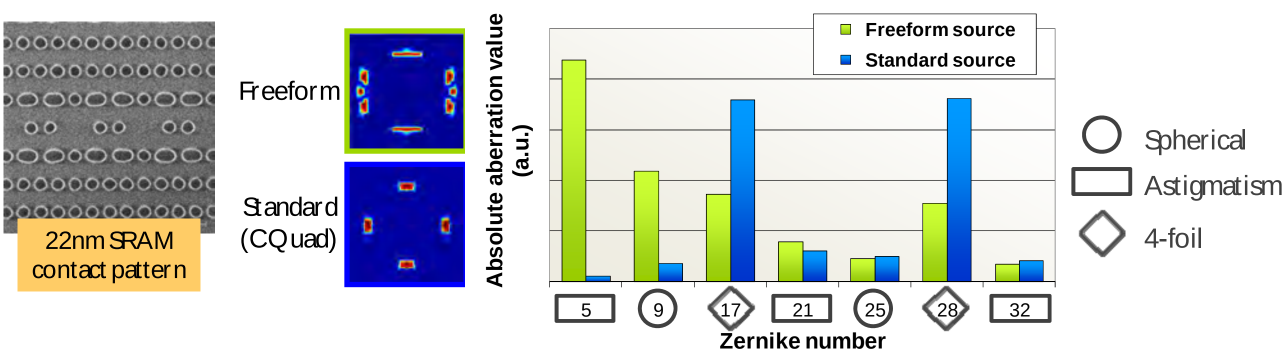

Figure 7. A simulated comparison of Zernike drifts between a freeform source and a standard source for the given use case of an SRAM contact pattern.

This data shows how the freeform versus standard source for a given application leads to a different distribution of the aberrations, however over the same Zernikes and without inducing particular increased aberration levels. In other words, the use of a freeform source does not lead to additional LH issues as compared to standard sources.

Note, however, that the above sources are both XY symmetric, like the printed pattern, which is why only the XY symmetric (non-rotated) Zernikes are induced. In the following section, aberrations induced by rotated sources (and their correction) are considered.

3.2 Illumination sources without XY symmetry

Rotated sources are point symmetric around the source center, but do not have XY symmetry. Using the lens heating simulation module an assessment is made of the lens heating effects of a dipole source, rotated over 0 deg (Dipole X), 15, 30, 45, 60, 75 and 90 degrees (Dipole Y). For a particular heat load and reticle, the simulated wave fronts without correction, and with correction from both ALC and FlexWave are shown in Figure 8.

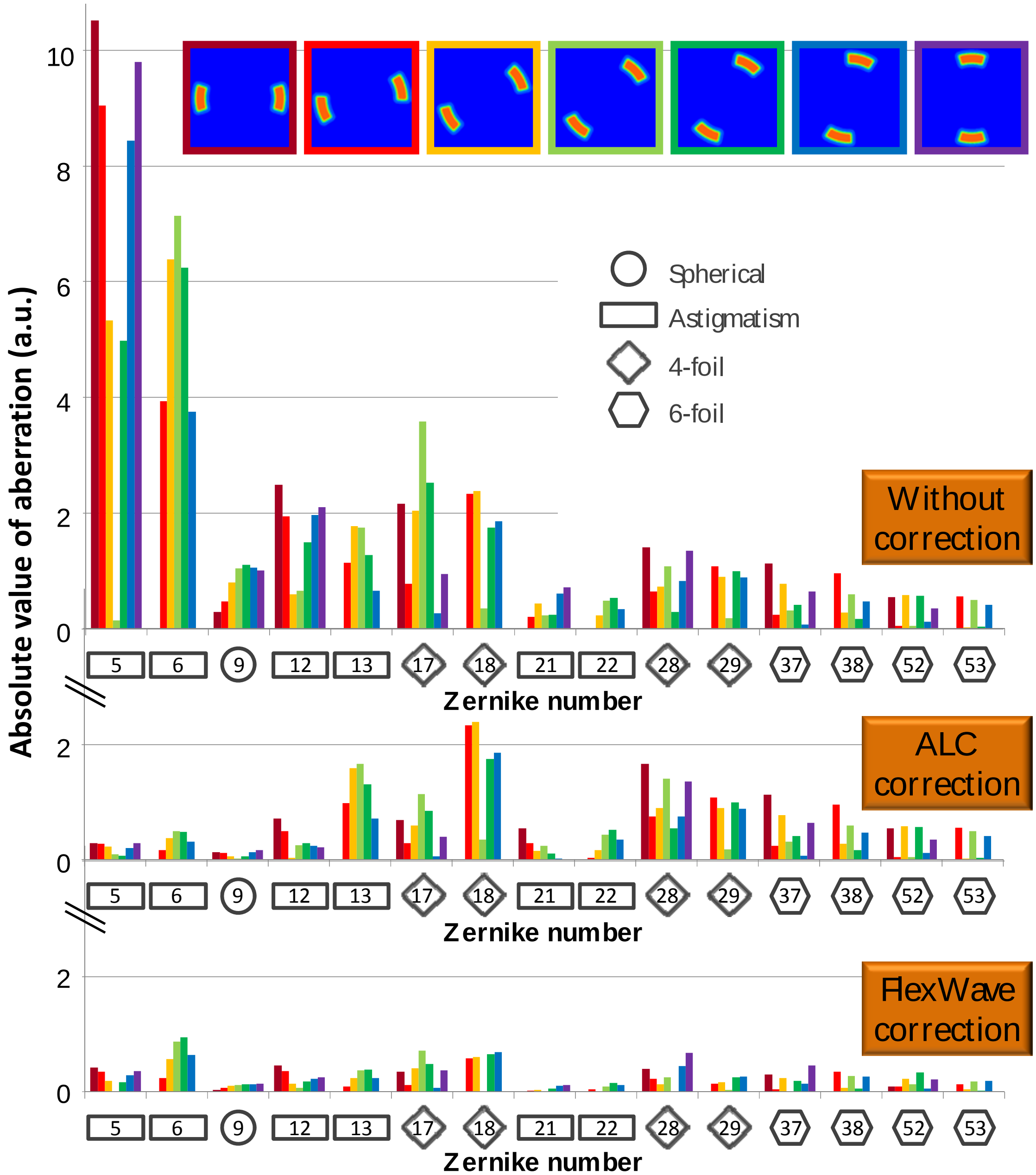

Figure 8. Comparison of uncorrected and corrected Zernike levels excited by dipoles rotated over various angles.

From the Figure, it can be seen how the rotated sources excite 'rotated' aberrations, like Z6, Z13, Z18, etc… E.g. under exact 45 degrees the Z5 term is diminished at the expense of Z6. Using the traditional ALC manipulators, the bulk of the dominant low frequent aberrations are removed. Using FlexWave, the largest correction potential is obtained, with capability of correcting up to Z64.

When two additional poles are brought in to form a squeezed CQuad source, the relative importance of lower frequency aberrations is reduced by a factor of 2~3. The simulation results of these sources are shown in Figure 9. Indeed, because the power is spread over the lens, the overall lens heating effect is reduced. Dipole-like sources give rise to the most pronounced aberration levels. From a similar comparison between the ALC and FlexWave corrections, it is clear that the latter is the most versatile lens heating control tool.

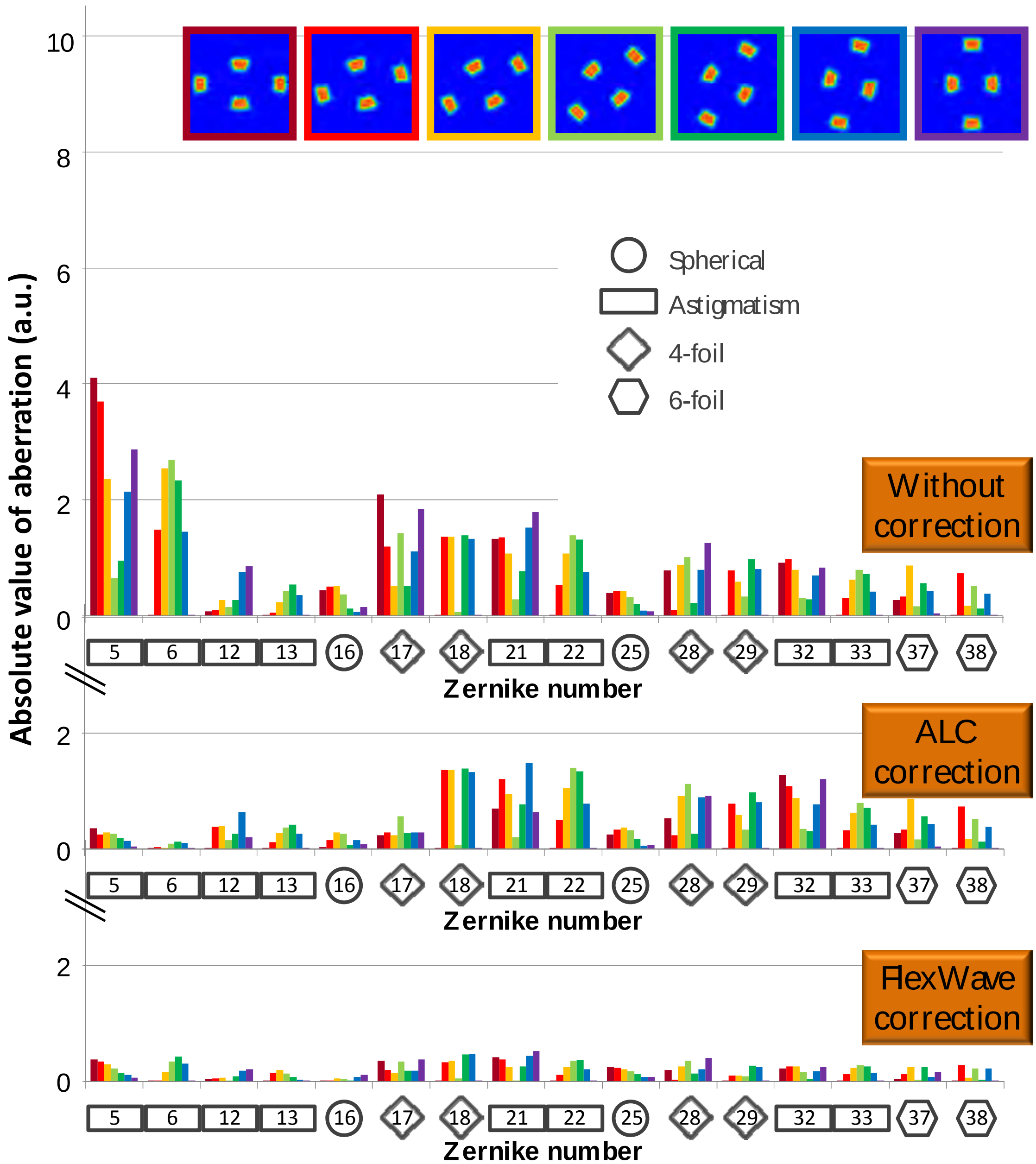

Figure 9. Comparison of uncorrected and corrected Zernike levels excited by rotated squeezed CQuad sources.

3.3 Measured versus simulated Zernikes

To assess the accuracy of the above Zernike prediction, the 15° rotated dipole source is created with the FlexRay system, and used in a 25-wafer lot exposure with a high dose to obtain measured aberrations. In parallel, the exposure conditions were entered in the ASML BRION lens heating simulator package to model these hot state aberrations.

The reticle that is used is a test reticle without a distinct diffraction. This makes the diffraction pattern and the original source shape to be the similar from a lens heating perspective. Figure 10 shows the source as well as the calculated diffraction pattern. The good match of the data in the graph shows how the modeling could well predict all hot state aberrations. As such, this demonstrates the capabilities of the computational LH calibration also for non-standard sources.

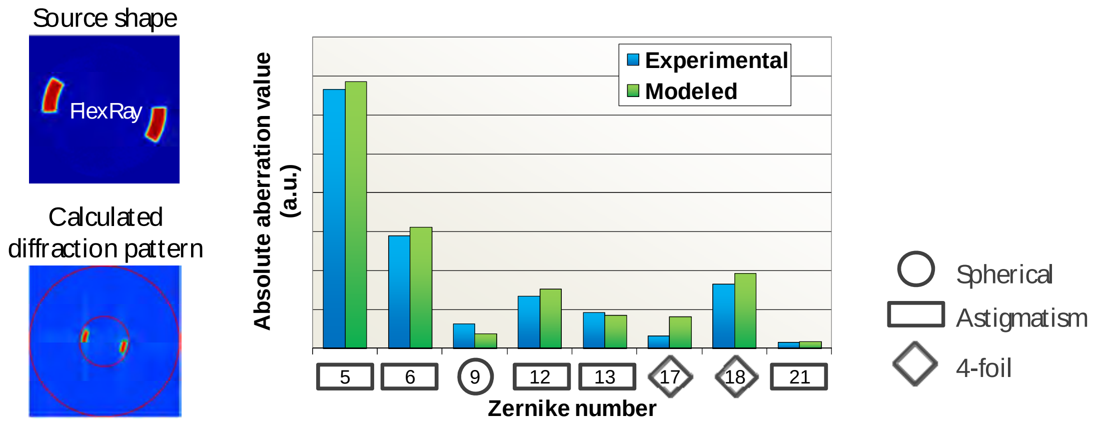

Figure 10. Comparison of measured and simulated Zernikes induced by a rotated dipole, which is a non-standard source.

CONCLUSIONS

The paper makes an assessment of advanced LH calibration and correction on ASML immersion scanners. First, experimental proof of lens heating correction is provided, both in terms of hot state wave fronts and CD drifts. In that, the correction provided through computational calibration yields similar correction results as correction based on inline calibration. This proves how the LH simulation tool in the ASML BRION litho simulation environment is a powerful tool for doing offline calculation of lens heating control parameters, and even to assess potential lens heating issues before production masks are manufactured. There is a good agreement between simulated and measured Zernikes.

Next, a modeling study was performed to assess lens heating effects for freeform or non-traditional source shapes. Compared to standard source shapes, freeform sources do not lead to additional lens heating issues. FlexWave shows a large correction potential (up to Z64), even for freeform sources without XY symmetry (like rotated sources) which give rise to wave fronts extending to high-frequent aberrations.

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